NBS TECHNICAL NOTE 665

U. S. DEPARTMENT OF COMMERCE / National Bureau of Standards

A Pyroelectric Power Meter for the Measurement of Low Level Laser Radiation

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A Pyroelectric Power Meter for the Measurement of Low Level Laser Radiation

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FOREWORD

The decision to develop the laser power meter described here resulted from need with the laser industry for a rapid, convenient means of low level measuring laser power. It was originally encouraged by T. W. Russell who was responsible for the Laser Measurement Assurance Program. The work was performed under the supervision of R. J. Phelan, Jr., Optical Electronics Program Leader. Others who gave substantial assistance to the project were L. O. Mullen, K. W. Pyatt, G. P. Klein, Y. Beers, and Debra Deichman.

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C. A. Hamilton and G. W. Day

A 1 cm^2 plastic (PVF_2) Pyroelectric detector, developed in this laboratory, has been applied to measure low level laser power. The result is a compact instrument which has a low noise equivalent power (10^{-8} W/Hz$^{\frac{1}{2}}$), and fast response (1 s averaging time), and which is precise ($\sigma \sim \pm$ 1%), uniform ($\sim \pm$ 1%), and inherently free from short term drift. This note describes the fabrication of the detector, the design of the instrument, and the results of an extensive evaluation of three such instruments.

Key words: Laser; power; pyroelectric.

1. Introduction

As a part of research program to develop high detectivity, large area pyroelectric detectors required by certain problems in laser metrology, we have designed, constructed and evaluated a transfer standard type of Laser Power Meter. This instrument is fast, precise and operates at low power levels. In this note we present the design details and evaluation results on three of these instruments.

The detector utilized in these instruments is based on the pyroelectric effect in PVF_2 (polyvinylidene fluoride) and has been under

development in this laboratory for several years. The devices have an active area of 1 cm^2. They are inherently uniform (~ ± 1%) over their surface and have a large dynamic range. Because they are thermal detectors, their spectral response is determined entirely by the absorptivity of their surfaces (typically gold black). For their size, these plastic pyroelectric detectors have a noise equivalent power which is unmatched by any other thermal detector (1-2 $nW/Hz^{\frac{1}{2}}$ at low frequencies).

2. Detector Design and Fabrication

Figure 1 shows the details of the detector assembly. The plastic used is 6 μm thick PVF_2 (polyvinylidene fluoride).[1-5] Nickel films, 0.01 μm thick, are vacuum deposited on each side of the PVF_2 so that circular overlapping electrode areas of 1 cm^2 are formed.

The circular area is then coated with a highly absorbing gold black layer.[6,7] This is accomplished by mounting the detector 7 cm above a gold filled tungsten filament in a sorption pumped vacuum system. The system is pumped to about 10^{-3} torr (1 torr = 133.3 N/m^2) and back filled to 1.5 torr with high purity nitrogen. Gold is then evaporated until a resistance monitor in the vicinity of the detector reads about 100 ohms/square.

Contact to the nickel electrodes is made through conducting epoxy to metal rings on either side of the plastic. Since the epoxy tends to weaken the dielectric strength of the plastic, the front contact points are rotated 90° from the back contact points. This keeps the weakened areas of the plastic well separated and prevents breakdown during the poling process.

The detectors are poled[5] in a three step process: (i) the device is placed in an oven at 100 °C and allowed 5 minutes to reach the oven temperature, (ii) a voltage of 800-1000 volts (1.3 - 1.6 x 10^6 V/cm) is applied across the nickel electrodes for another 5 minutes, (iii) the device is removed from the oven and allowed to cool for 5 minutes with the field still applied, after which the voltage is reduced to zero.

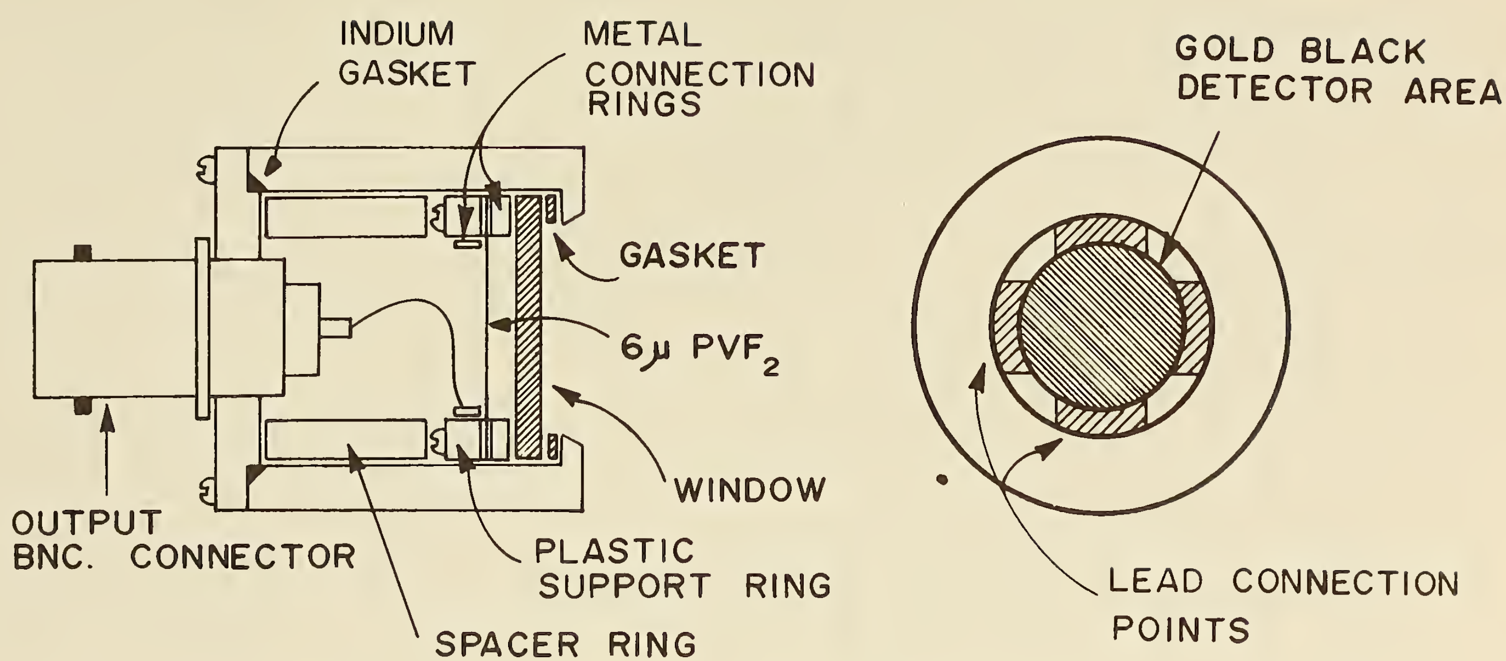

Figure 1. Pyroelectric detector design.

Finally, the detector is mounted in a sealed case with a glass window. (For infrared measurements the window is usually hot pressed zinc sulfide.) The window is ground to a 1° wedge to eliminate transmission variations due to interference between front and back faces. A good hermetic seal on the case is crucial in eliminating detector response to acoustic sources.

Before one of these detectors is accepted for use in a power meter, it must pass three tests: (i) its responsivity must be between 1.3 and 2.2×10^{-6} A/W, (ii) its response must be uniform to ± 1% over its receiving area, and (iii) its NEP must be less than 5×10^{-9} W/Hz$^{\frac{1}{2}}$ at 10 Hz. Detectors meeting this last condition allow the power meter to meet its designed resolution of 1×10^{-8} watts with a one second averaging time.

Measurements on a number of detectors have shown a typical responsivity temperature coefficient of + 0.5%/$^{\circ}$C. Thus, there is a calibration change with room temperature as well as nonlinear behavior when the applied radiation begins to warm the detector more than a few degrees. Both of these problems are discussed in more detail in the following sections.

3. Instrument Design

Almost all radiometric instruments[8] are calibrated at one or more power levels against some standard optical source. Thus, if the detector and its associated electronics are linear, the radiometer will be calibrated for any input power. Figure 2 shows how this method is used in our power meter.

Since the pyroelectric detector responds only to changes in its temperature, the input radiation must be chopped. This is accomplished by a motor driven mechanical chopper with a 1.25 cm diameter aperture. The detector output is amplified and synchronously demodulated to produce a dc output proportional to the chopped radiation. Since the chopper is a separate unit, the field of view may be arbitrarily narrowed by increasing the distance between chopper and detector. This feature is particularly useful in discriminating against background radiation.

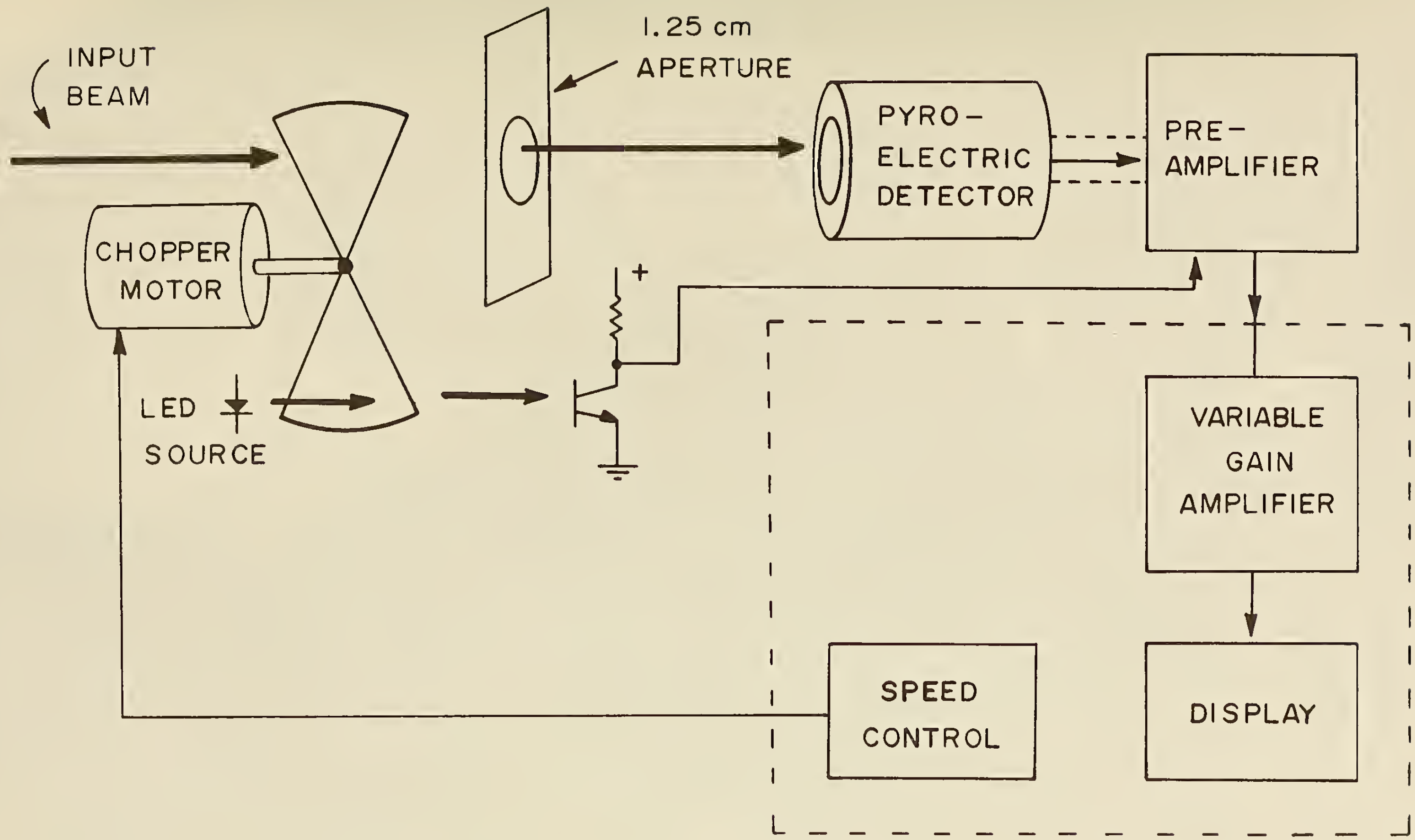

Figure 2. System block diagram.

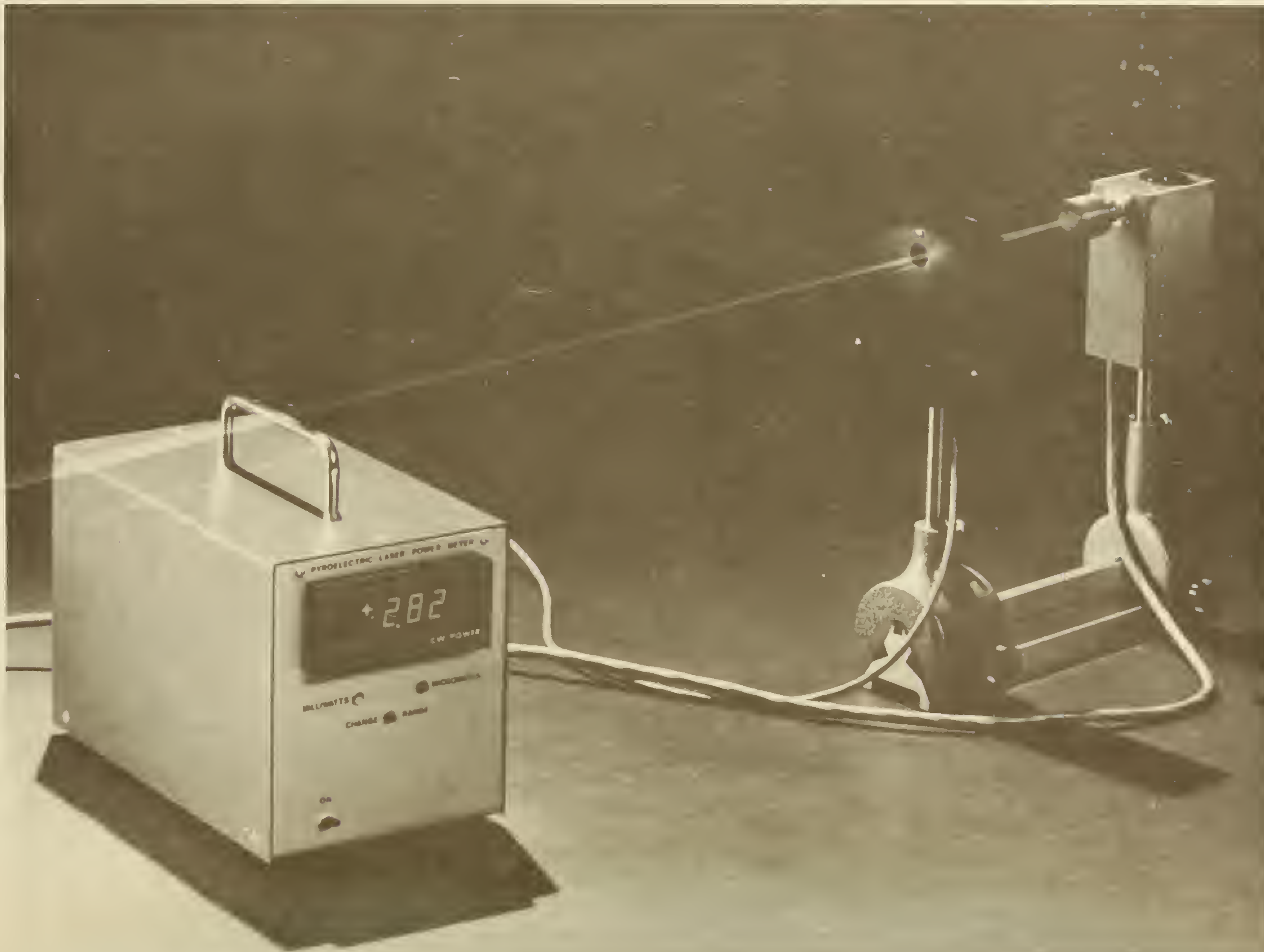

Figure 3. Pyroelectric Laser Power Meter being used to measure the power from a He-Ne laser. The reflections from the wedge window are clearly visible.

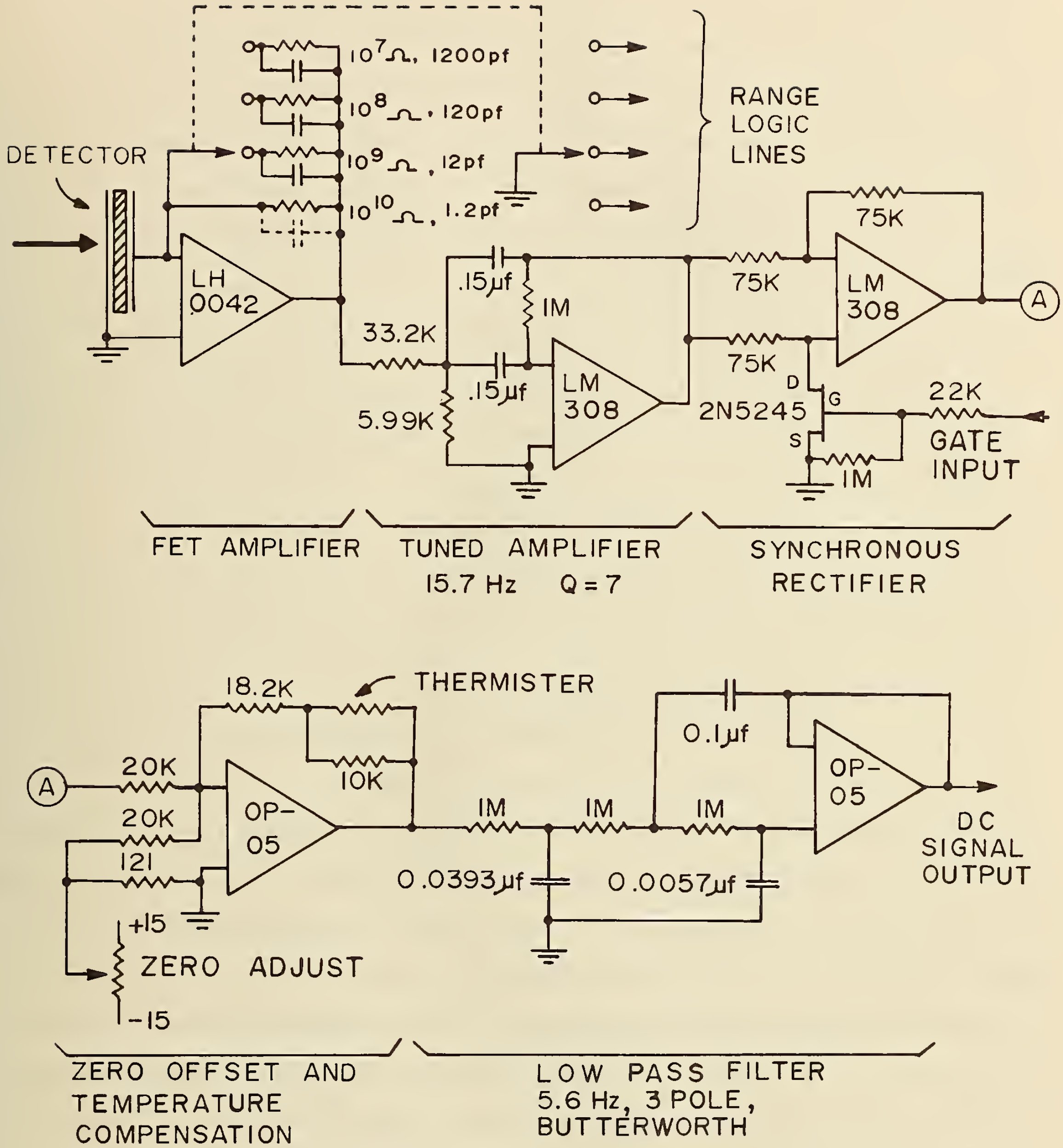

Figure 4. Preamplifier converts low level detector output into a dc voltage.

The angular width of the chopper aperture relative to the blade is 20°. Thus the output wave form of the detector is dependent on the intensity distribution over the aperture. Since the preamplifier responds only to the fundamental component and the instrument is calibrated for a narrow beam at the aperture center, two types of error may occur. (1) If a narrow beam passes through the aperture θ degrees off center, the error is 1-cos θ with the worst case being 1.5%. (2) If the aperture is uniformly illuminated the error is $1 - \frac{\sin\theta}{\theta}$ or a worst case of 0.5%.

The dc preamplifier output goes through a variable gain amplifier to a 3½ digit display. Calibration is achieved by applying a known amount of power and adjusting the gain to obtain the correct reading. Figure 3 is a photo of the complete instrument as it might be used to measure the power of a He-Ne laser beam.

The following paragraphs describe in more detail how each part of the instrument operates.

3.1 Preamplifier

The preamplifier circuit shown in figure 4 converts the square wave current output of the detector into a dc level. The designed dynamic range is 10^{-8} to 10^{-2} watts corresponding to detector outputs of 10^{-14} to 10^{-8} amperes. Because of noise considerations, it is impractical to build a single gain amplifier with six decades of dynamic range. Thus, the first stage is a FET input, current mode, operational amplifier whose gain is determined by one of four feedback resistors. These resistors have a temperature coefficient of 0.2%/C° and partially compensate for the detector temperature coefficient. The switch which selects the resistor also provides logic signals to indicate the range setting to the display part of the instrument. The feedback capacitors on the upper three ranges match the amplifier time constant caused by parasitic capacitance on the lowest range. The next stage is a narrow band amplifier which is tuned to the chopper frequency. The sine wave output of stage 2 is synchronously rectified in

stage 3. This is accomplished by switching the gain between +1 and -1 with the FET switch. The square wave gate for the switch is synchronized with the chopper and has an adjustable phase delay. The next stage provides a zero adjust for the demodulated detector output, and it compensates for the remaining temperature dependence of the detector by adding a temperature coefficient of -0.3%/$^{\circ}$C. Figure 5 shows how the thermister in the feedback network performs this task. Since the thermister is thermally tied to the preamp case, measurements of the highest accuracy require that sufficient time be allowed for the detector-preamp assembly to reach the same temperature. The final stage is a sharp cut-off low pass filter which removes the ripple from the demodulated signal.

3.2 Chopper and Speed Control

Since the preamplifier is tuned to a specific frequency, it is important that the chopper run at a precise speed. This is accomplished by the speed control circuit shown in figure 6. In addition to intersecting the laser beam, the chopper wheel also passes through an LED-phototransistor pair. The square wave output of the phototransistor is amplified and used to trigger a pulsing circuit. This circuit creates a stable 3 ms pulse whose height and width are independent of frequency. Thus, when the pulses are averaged, the resulting dc level is proportional to the chopper speed. This level is compared to a reference and the amplified difference signal drives the motor. The servo loop described above controls the chopper speed to better than 0.1 Hz.

A second part of the circuit provides the delayed reference square wave used in the preamplifier synchronous rectifier. The rising edge of the phototransistor output triggers a one-shot with adjustable pulse length. The falling edge of the one-shot output triggers a second one-shot also with adjustable pulse length. The first pulse length is set to the desired delay time and the second is set to one half the chopper period. Thus, the output of the second one-shot is a delayed reference square wave.

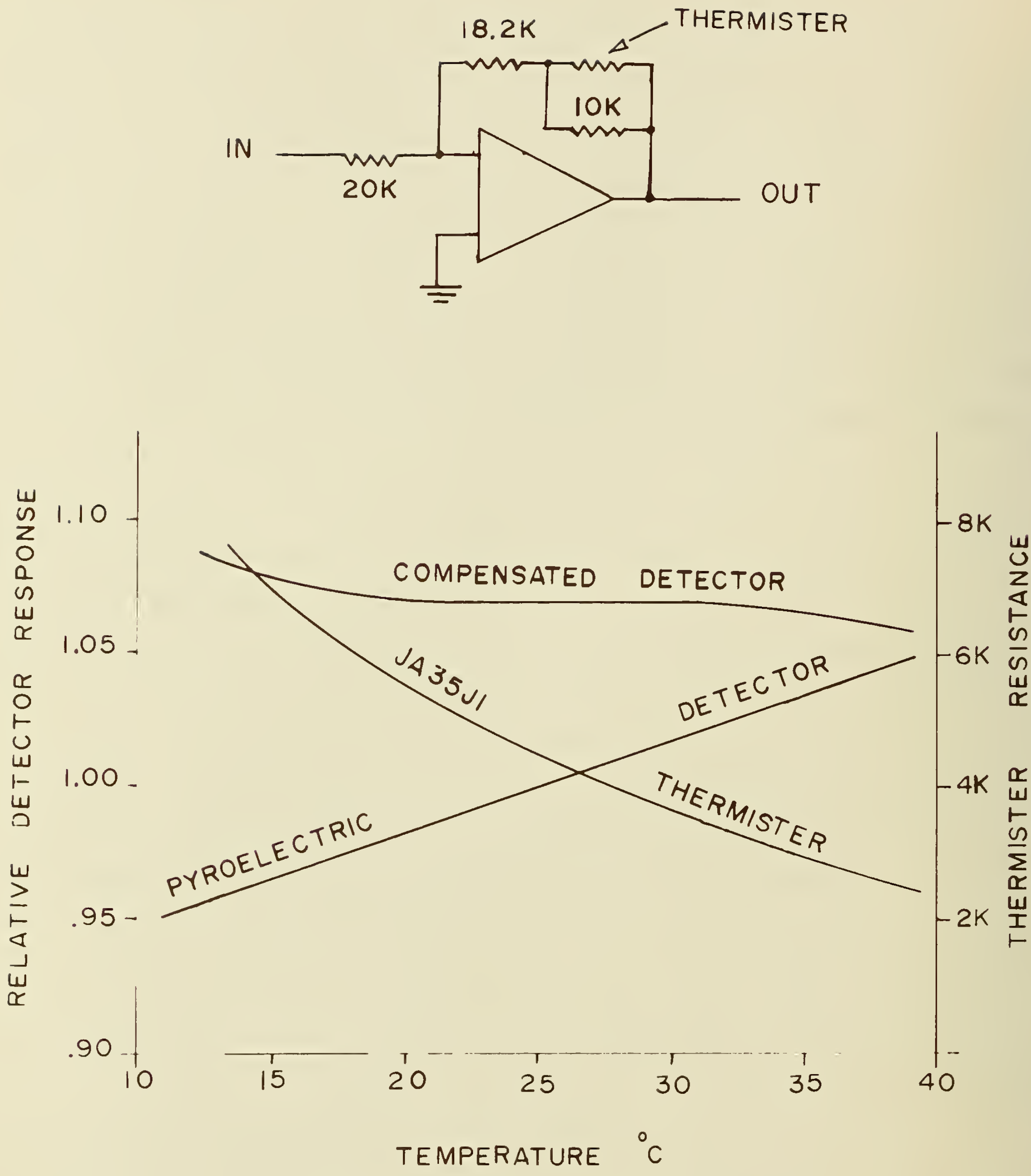

Figure 5. A thermister in the preamplifier compensates for the detector temperature coefficient.

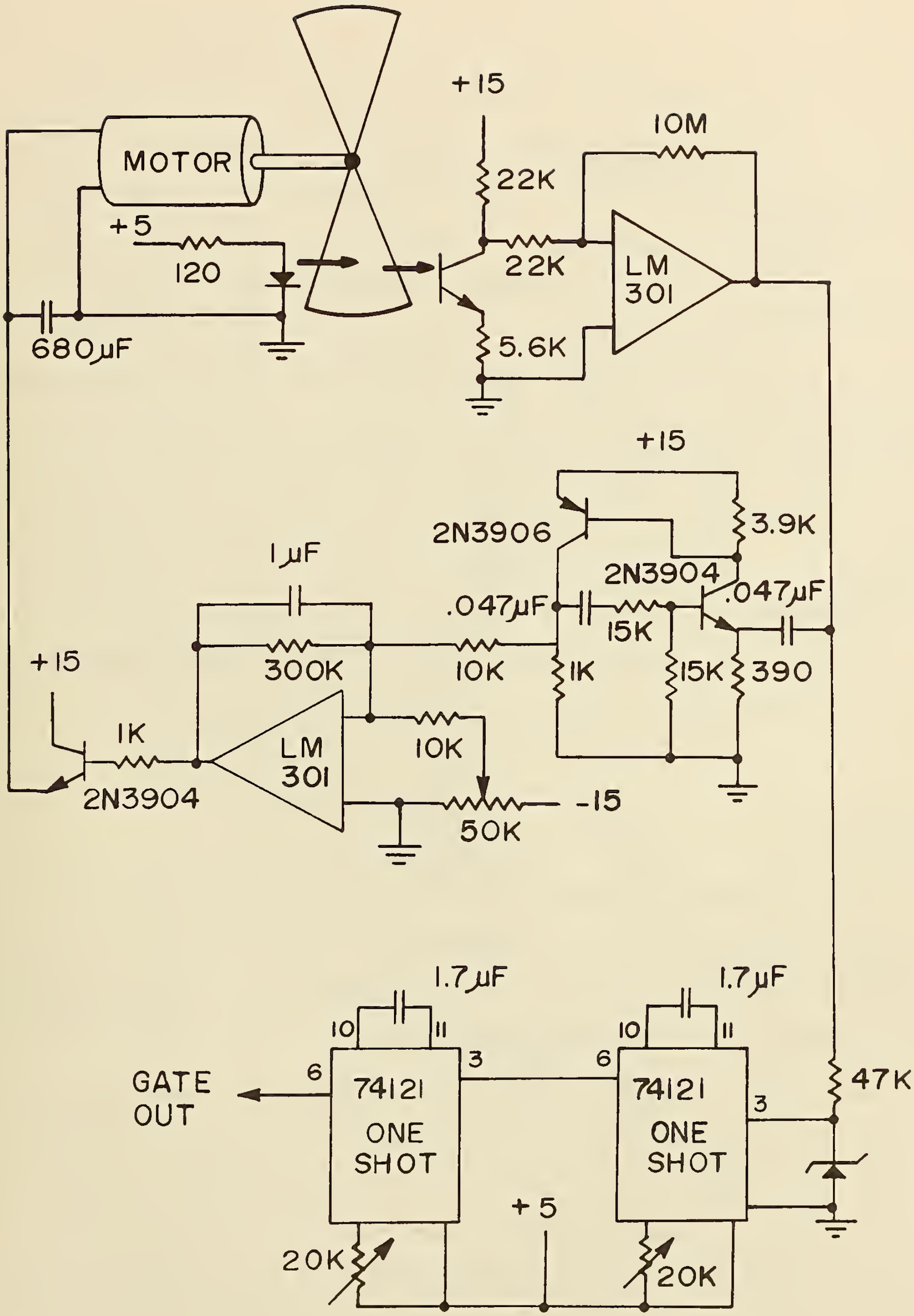

Figure 6. Chopper speed control and delayed reference square wave.

3.3 Readout Circuitry

As shown in figure 7, the readout circuitry begins with the analog and digital outputs of the preamplifier. The four digital lines give the range setting and are decoded to drive the display decimal point and a mW or μW indicator. The analog output of the preamp passes through the readout amplifier to the digital panel meter. Reed relays select a different feedback resistor for each range. These resistors are adjusted to make the system gain switch in exact decade increments. This compensates for any inaccuracy contributed by the switched preamp resistors. The input resistor to the readout amplifier is then adjusted to calibrate the whole system for a specific detector.

The output of the readout amplifier also passes through a voltage follower to an analog output connector. This allows the instrument to be used with a recorder.

4. Evaluation

Three Laser Power Meters of the type described in the preceding sections have been studied for a period of several months to assess their performance and limitations and to indicate their general utility for the measurement of low level laser power.

The accuracy of these instruments is principally dependent on extensive and careful initial calibration. We deal here only with relative measurements and hence obtain information about the precision of the instruments rather than the accuracy. Among the parameters affecting the overall precision are the alignment of the chopper and detector, detector uniformity, detector noise, temperature coefficient, linearity, and drift in detector responsivity.

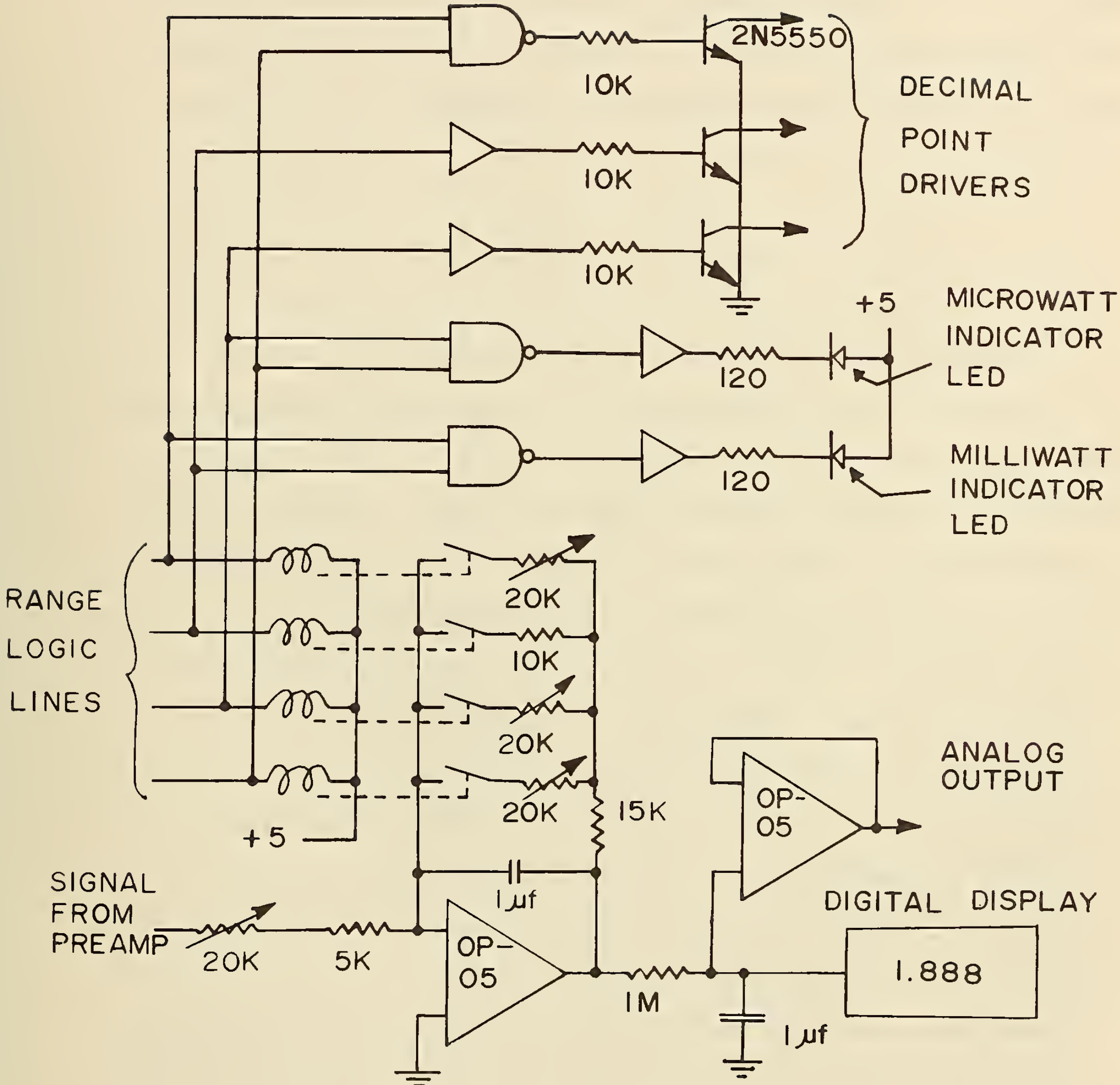

Figure 7. Readout circuit sets decimal point and calibrates the four ranges.

Most of the measurements were made on range 2 (200 μW F.S.). Based on design and experience with the instruments, it is expected that similar performance should be expected on range 3 (2 mW F.S.) and within the limits of detector linearity on range 4 (20 mW F.S.). Range 1 (20 μW F.S.) performance may not be quite as good as the upper ranges due to detector noise and limitations of background light.

4.1 Precision

The principal measurements were made with a commercial 2.4 mW ($1/e^2$ radius = 0.45 mm, divergence = 1 m rad) unpolarized He-Ne laser operating at 632.8 nm. The laser illuminated a wedged glass beam splitter at a distance of 1.6 m from the laser. The first surface reflection (angle of incidence = 3°) had a power level of about 100 μW. The chopper and detector of each instrument were alternately inserted into this reflected beam at distances from the beam splitter of 0.5 and 1.5 meters respectively. Alignment was achieved by visually centering the beam in both the chopper aperture and detector active area. Power transmitted through the beam splitter was measured with a silicon diode power meter.[9] The latter power meter was fixed in position to eliminate problems of detector nonuniformity and zero adjusted to compensate for room temperature fluctuations.

Data were normally taken daily and consisted of measurements of the reflected power by the three pyroelectric Laser Power Meters (P1, P2, P3), a measurement of the transmitted power (PSI), the date and temperature. Several people (some of them unfamiliar with the instruments) participated in the data taking to insert some human factors into the evaluation.

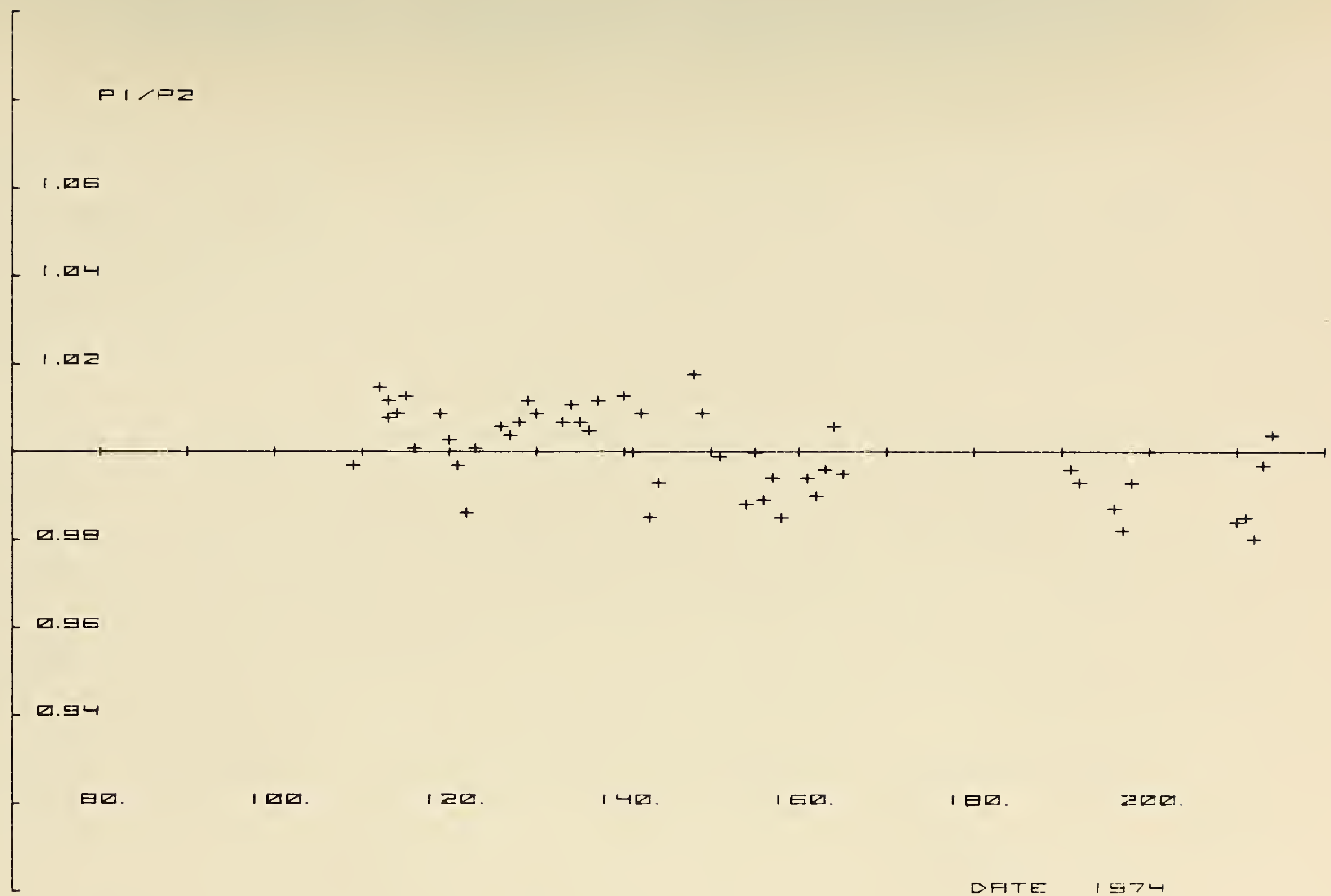

Figure 8. The ratio P1/P2 (divided by its mean) vs. the date on which the measurement was made.

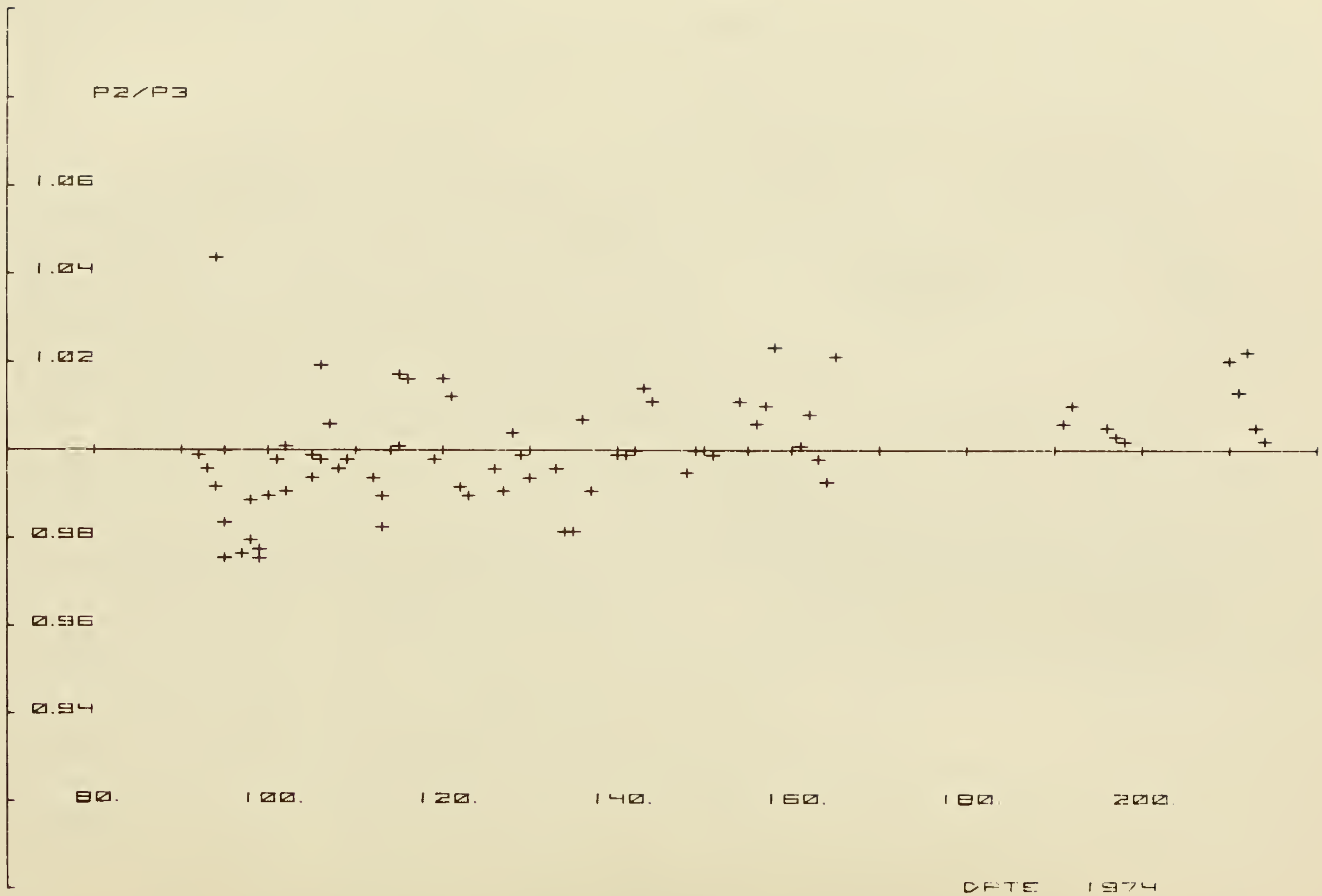

Figure 9. The ratio P2/P3 (divided by its mean) vs. the date on which the measurement was made.

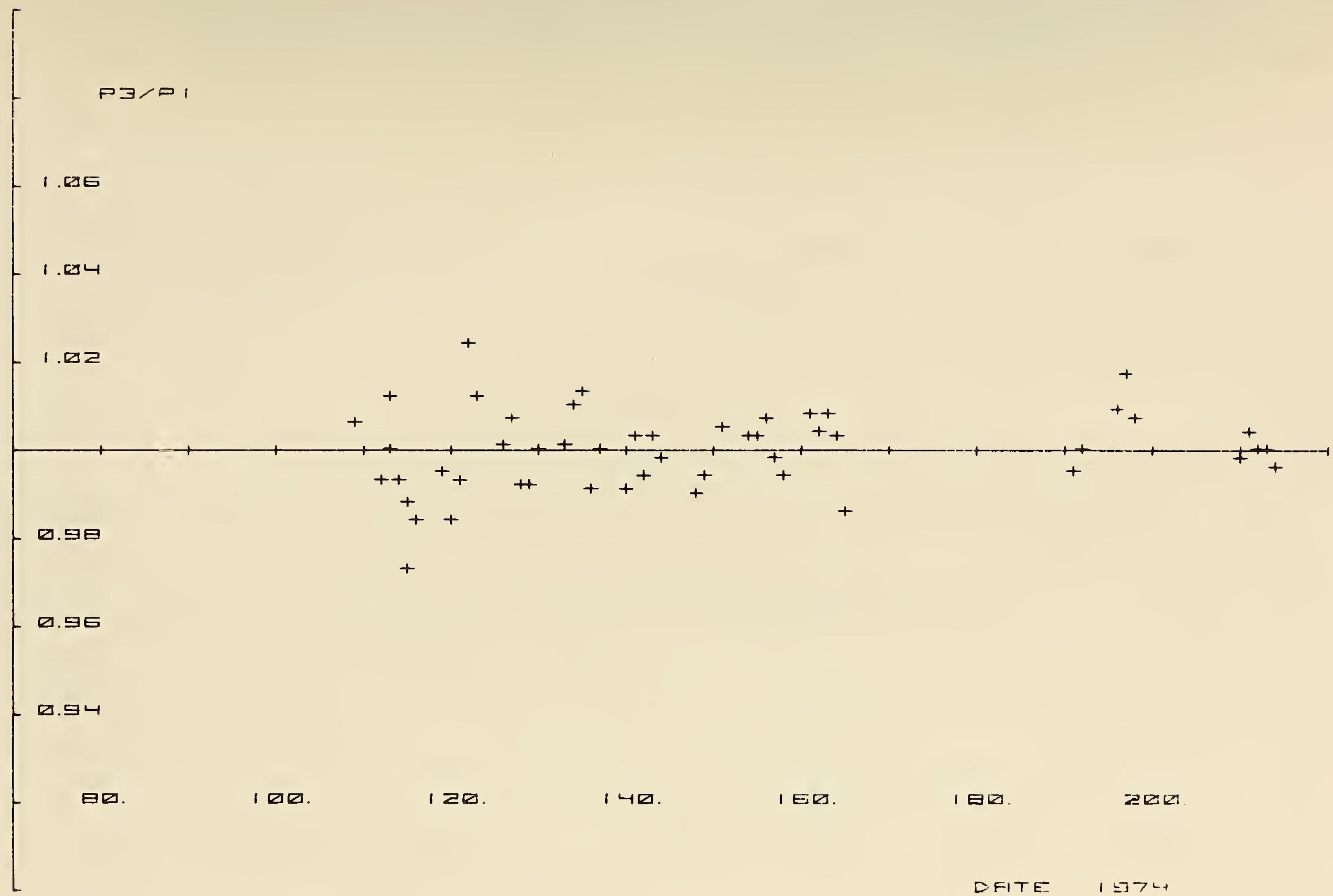

Figure 10. The ratio P3/P1 (divided by its mean) vs. the date on which the measurement was made.

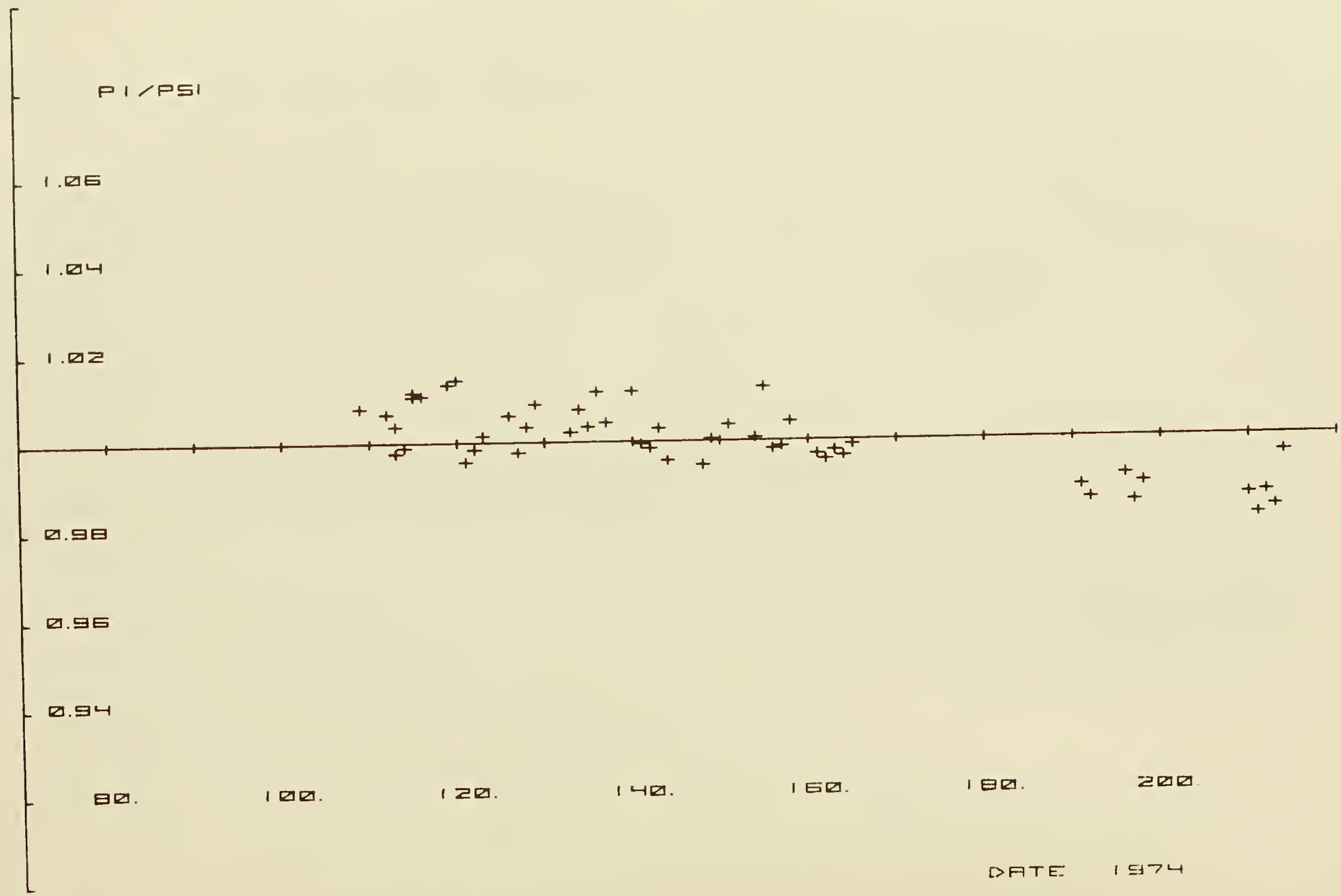

Figure 11. The ratio P1/PSI (divided by its mean) vs. the date on which the measurement was made.

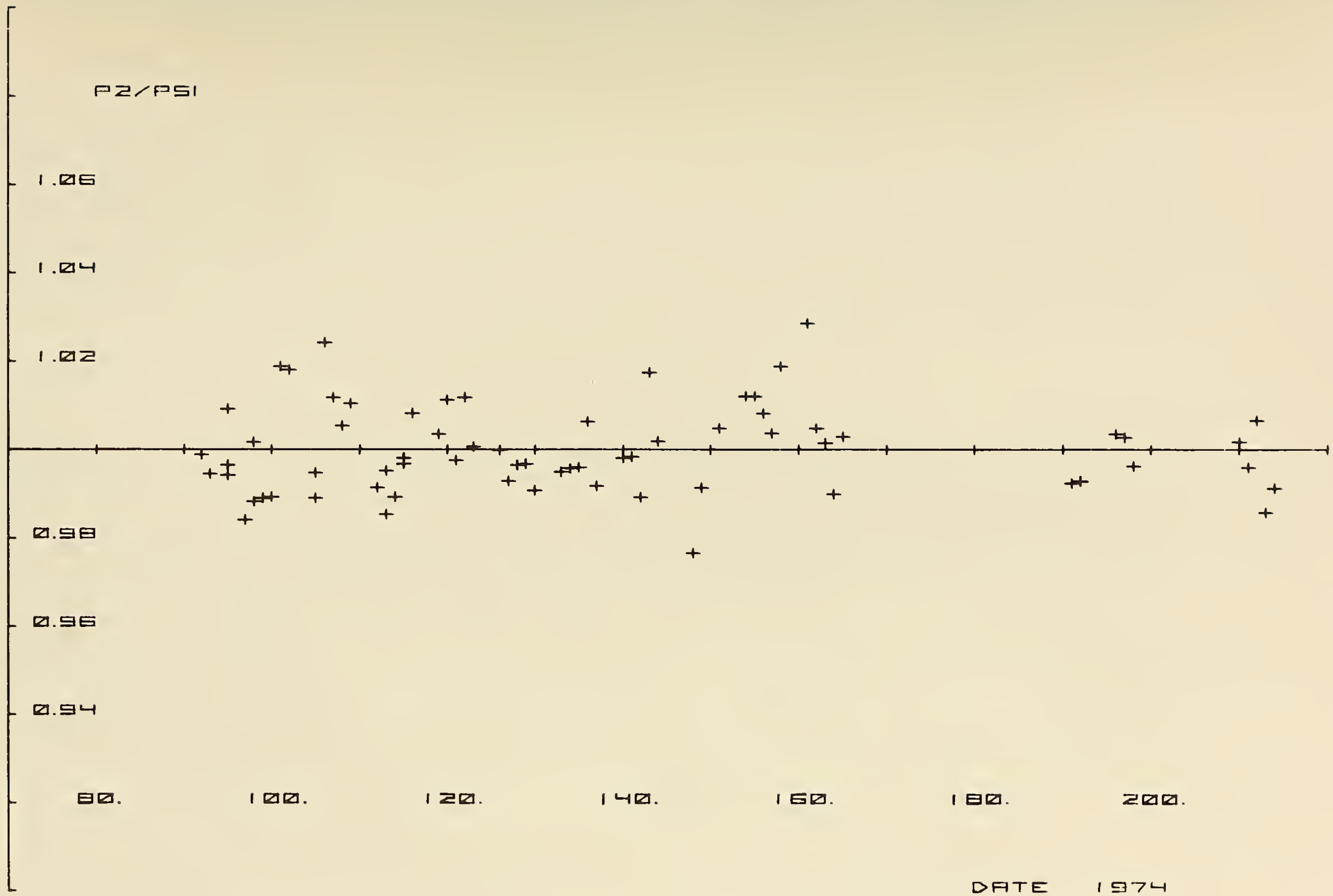

Figure 12. The ratio P2/PSI (divided by its mean) vs. the date on which the measurement was made.

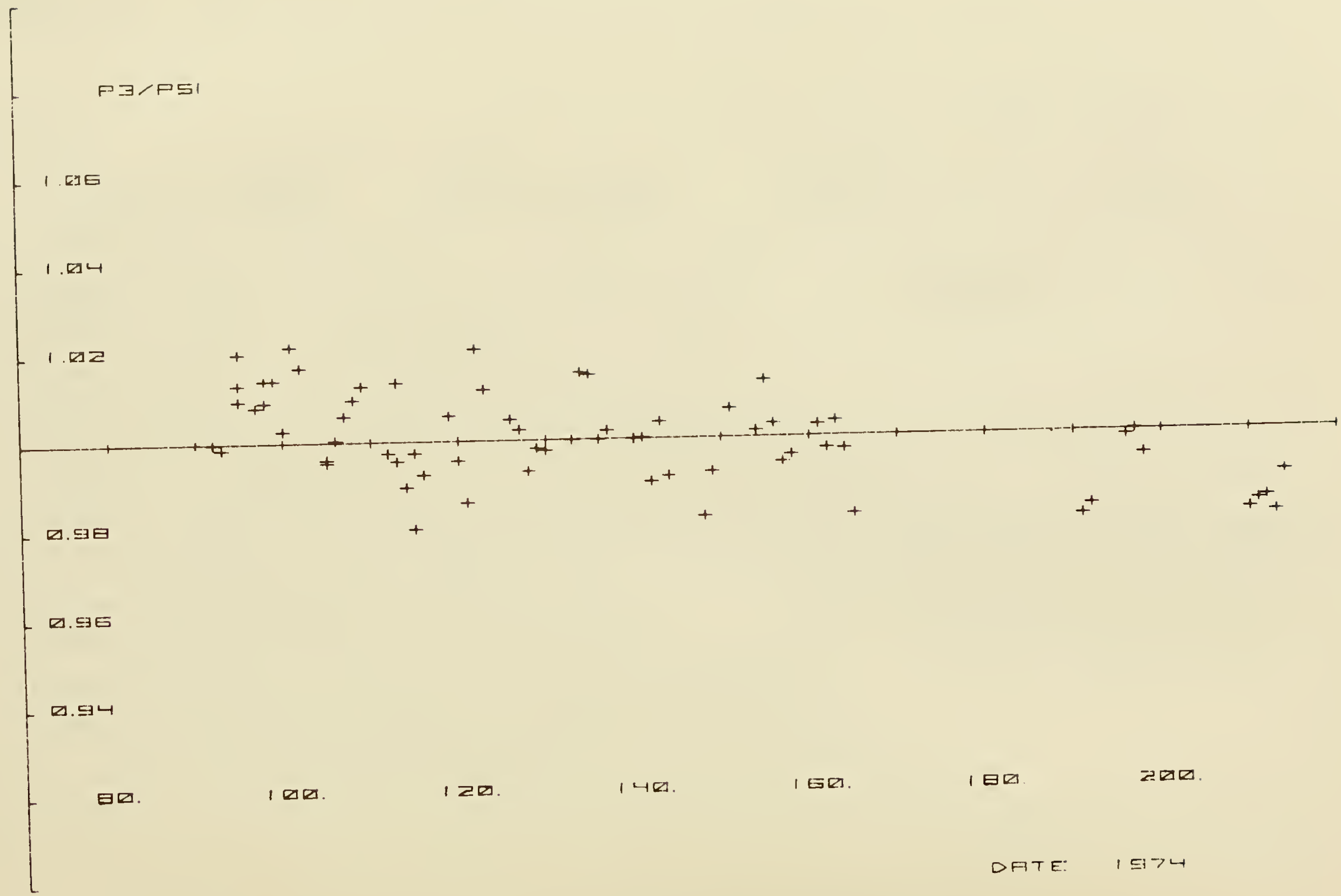

Figure 13. The ratio P3/PSI (divided by its mean) vs. the date on which the measurement was made.

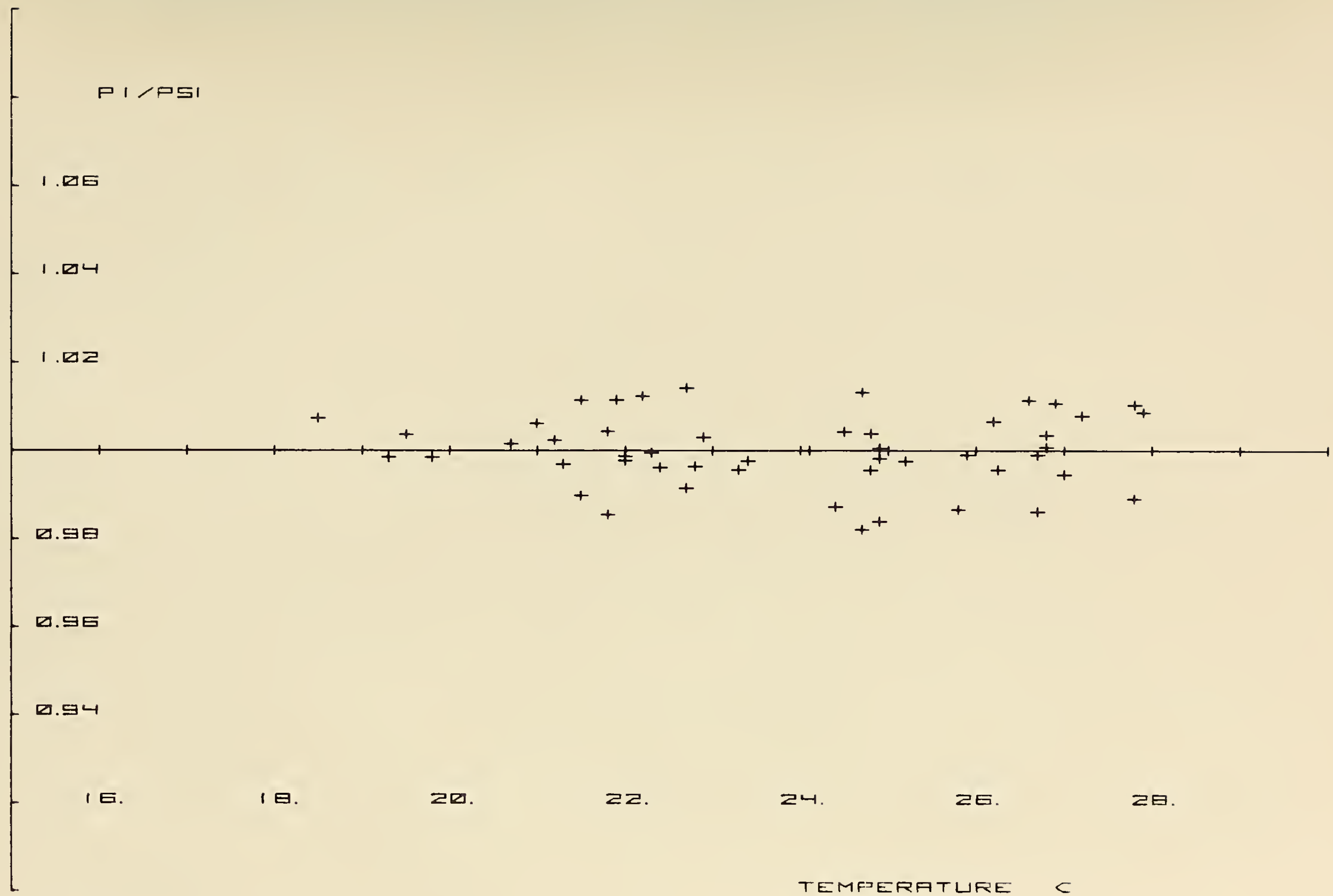

Figure 14. The ratio P1/PSI (divided by its mean) vs. the room temperature at the time of measurement.

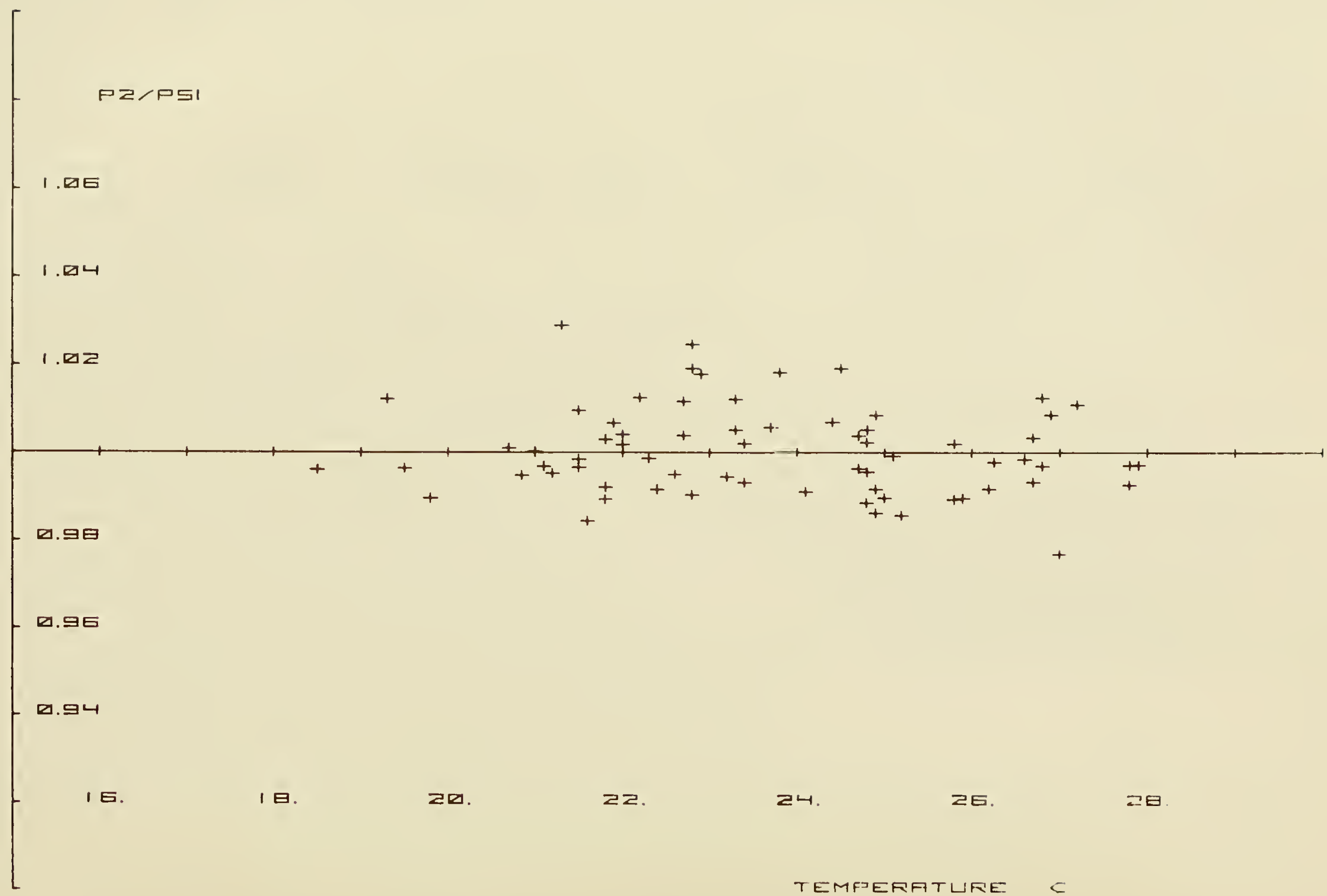

Figure 15. The ratio P2/PSI (divided by its mean) vs. the room temperature at the time of measurement.

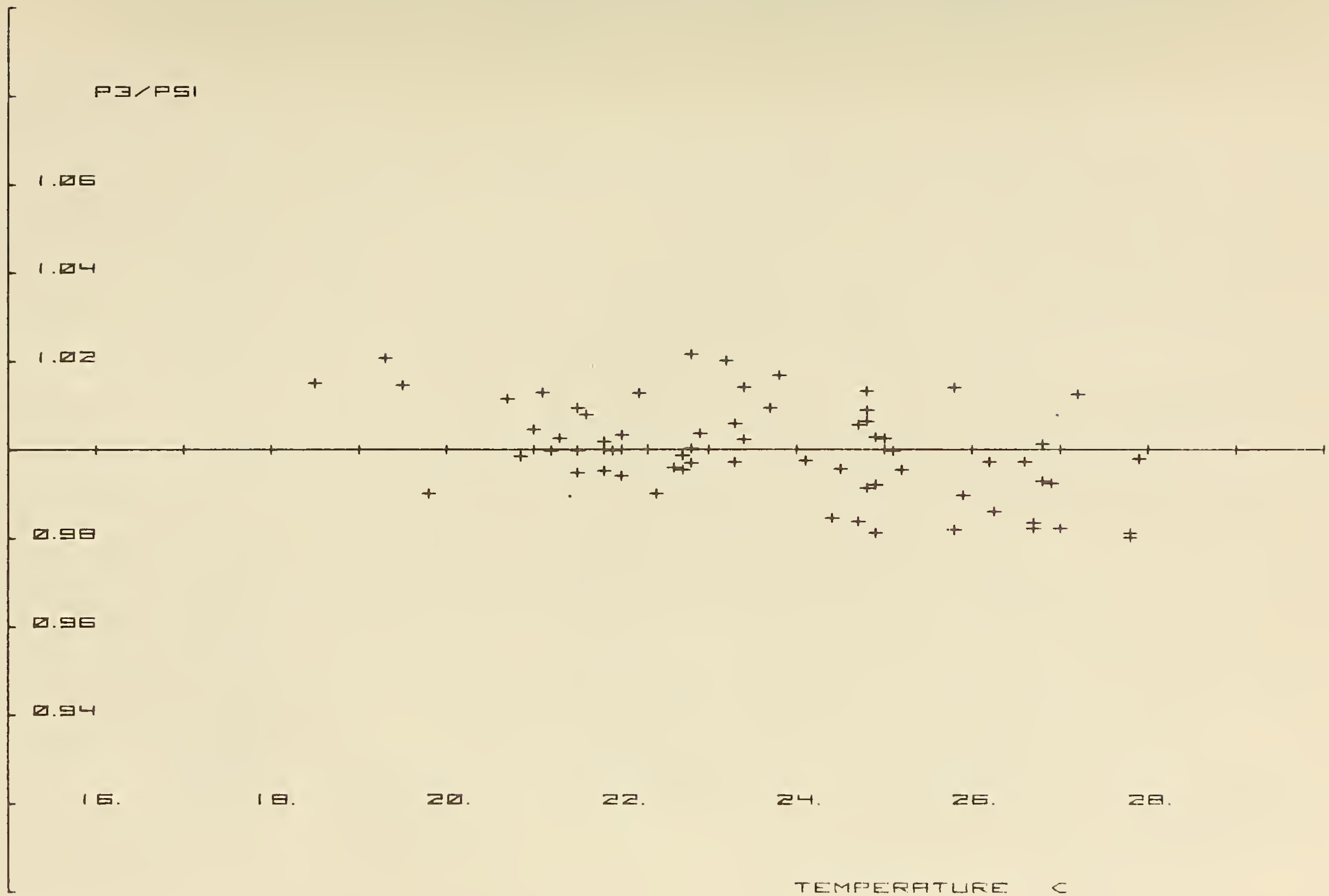

Figure 16. The ratio P3/PSI (divided by its mean) vs. the room temperature at the time of measurement.

	# Samples	σ	Slope day^{-1} (95% confidence)	Slope $^{o}C^{-1}$ (95% confidence)
P_1/P_2	51	0.98%	$(-2.0 \pm 0.7):10^4$	
P_2/P_3	73	1.25%	$(+1.5 \pm 0.8):10^4$	
P_3/P_1	51	0.92%	$(+0.6 \pm 0.8):10^4$	
P_1/Psi	51	0.81%	$(-2.0 \pm 0.5):10^4$	$(-1.6 \pm 9.3):10^4$
P_2/Psi	68	1.01%	$(-0.0 \pm 0.7):10^4$	$(-5.9 \pm 10.8):10^4$
P_3/Psi	68	1.05%	$(-1.7 \pm 0.6):10^4$	$(-25.0 \pm 9.8):10^4$

Figure 17. Analysis of the data from figs. 8-16.

Reduced data consisted of the ratios P1/P2, P2/P3, P3/P1, P1/PSI, P2/PSI and P3/PSI. There are plotted vs. date and temperature in figures 8 to 16 and the results are summarized in figure 17.

Analysis of this data for precision gives a typical standard deviation of 1%. Because the measurements are made sequentially, the results are dependent on the stability of the laser. The extent to which this increases the scatter in the data is not readily measurable. In a separate experiment, with instruments 2 and 3 in fixed alignment, simultaneously measuring the reflected power from two nearly identical beam splitters, the ratio P2/P3 showed a standard deviation of 0.25%. The difference between this number and the 1.25% from figure 17 is a measure of the scatter due to the combined effects of detector non-uniformity and laser fluctuations. We thus believe that the standard deviation numbers presented in figure 17 are conservative as a measure of system performance. Uniformity is discussed further below.

Linear regression analysis for temperature coefficient gives a statistically significant slope only for the ratio P3/PSI. As noted previously, the electronics of all three instruments were designed to compensate for a temperature coefficient of the detector responsivity of + 0.5%/^{o}C, even though some variation in the temperature coefficient of the responsivity from detector to detector was known to exist. The detector of instrument 3 evidently has an inherently low temperature co-efficient. A better approach would be to match the compensation of the detector.

Analysis for long term drift shows a statistically significant slope for two of the instruments (1 and 3) relative to the silicon diode power meter, of 1-2 parts in 10^4 per day. Power meter number 2 does not show this drift. A drift of this magnitude is not of extreme concern in an instrument which is used as a transfer standard but needs to be considered. The source of this drift has not yet been isolated but most likely relates to aging of either the detector itself or of the high value feedback resistors used in the preamp. Measurements of

typical feedback resistors ranging over 45 days indicate that these components are probably not responsible for the drift. Long term experiments, now in progress, are expected to further illuminate this matter.

4.2 Corroboration

Approximately 20 calibrations of a similar instrument against the NBS C-series calorimeter have been made by the Laser Parameter Measurements Group of NBS, Boulder. Analysis of this data shows a standard deviation of 1.27%. This data was taken on range 3 (2 mW F.S.). It should be pointed out that this instrument was not one of the three evaluated above and had not had as thorough a check out as the other three.

4.3 Uniformity

A response map of the detector from instrument 1 using a beam diameter of ~ 0.3 mm is shown in figure 18. It is typical of the uniformity of these plastic pyroelectric detectors. Quantitative measurements yield uniformities (standard deviation for any array of 168 points covering roughly the central 2/3 of the area) of between 1.3 and 1.8% for these three instruments.

4.4 Spectral Response

As mentioned above, the spectral response of these instruments is determined by the absorptivity of the gold black on the detector and by the window transmittance. The absorptivity of the gold black is process dependent but based on comparisons with detectors having a known spectral response, it appears that the gold black is typically flat and highly absorbing in the visible and becomes less absorbing at

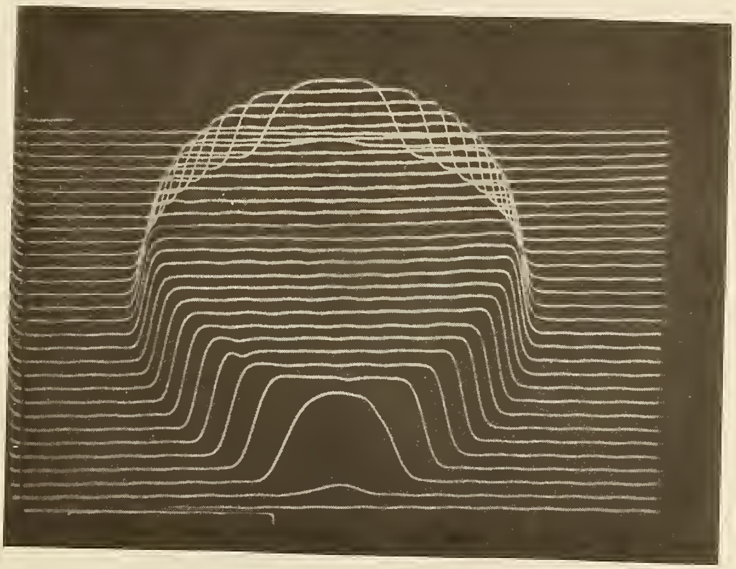

Figure 18. Response map of the detector from instrument 1.

wavelengths beyond 1 μm. A monotonic decrease in absorptivity between 1 μm and 25 μm of 50% is probably typical.

For the specific instruments tested, which had glass windows, the calibration should be independent of wavelength over essentially all of the transparent range of the window. At longer wavelengths, using a different window material, calibrations must be made at the wavelength of interest.

4.5 Linearity

Measurements of responsivity vs. temperature show that PVF_2 pyroelectric detectors may have a temperature coefficient of as much as 0.5%/°C at room temperature. Thus, when the applied power level is sufficient to raise the PVF_2 temperature more than a few degrees, the response will become nonlinear. This nonlinearity was measured as follows.

A nominal 10% transmitting neutral density filter was placed in front of one of the power meters. The filter was mounted on a swival base in such a way that it could be moved in and out of the beam in a reproducible fashion. Using a 2.0 mm diameter ($1/e^2$ points) 632.8 nm laser beam, a number of power measurements were made with and without the 10% filter. Figure 19 shows the filter input/output ratio as a function of the input power level. In order to avoid range to range errors, the measurement of each ratio was made without changing ranges on the power meter. This resulted in a rather poor resolution in the low power reading. The error bars are an indication of this resolution problem.

Assuming that the filter transmission is independent of power, the upward curve of the data is a measure of the nonlinearity in the detector. The threshold of nonlinearity is about 50 mW/cm^2. For the beam diameter of typical He-Ne lasers (~ 1.5 mm) nonlinearity begins at about 1 mW. At a power of 3mW, the error is about 4% and at 10 mW the error is 10%.

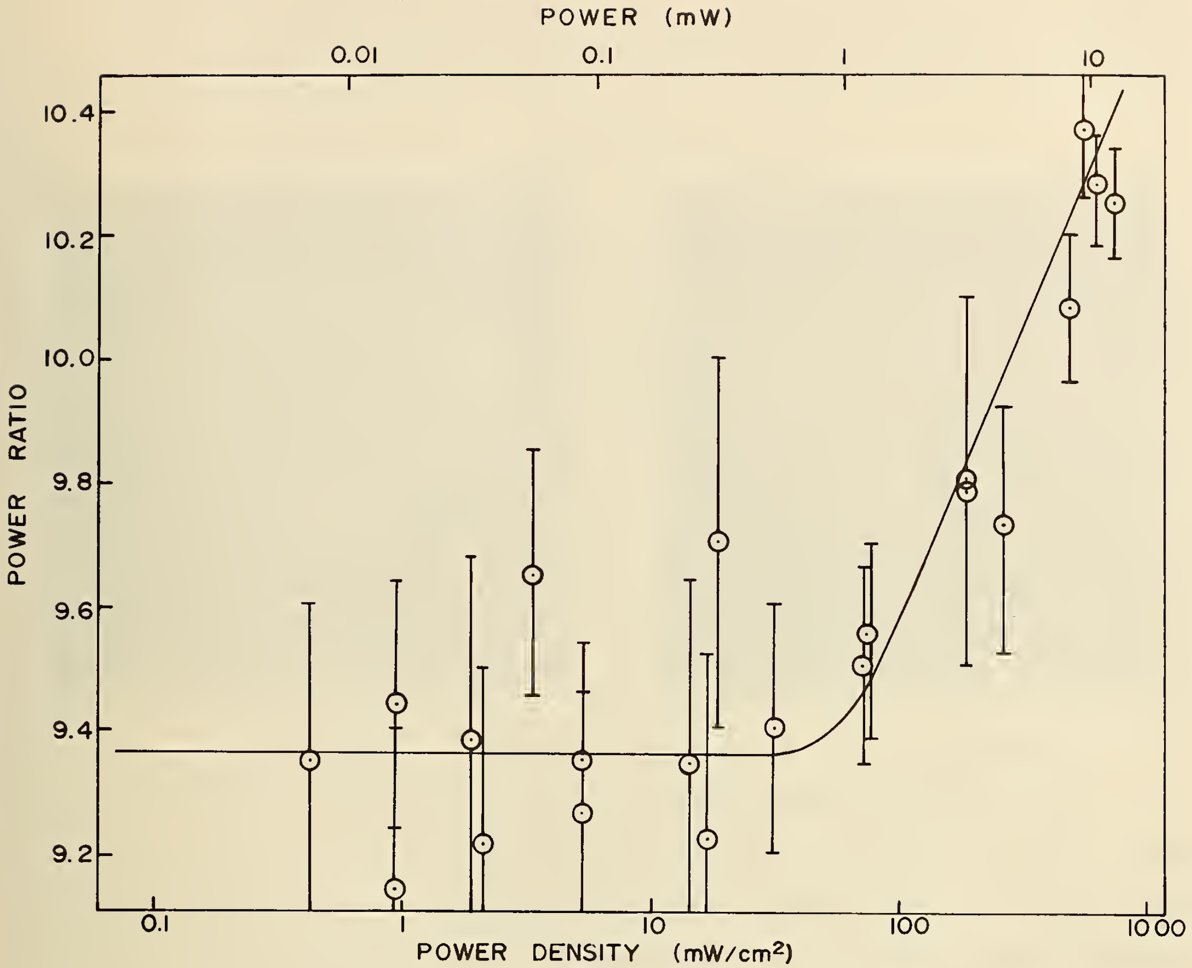

Figure 19. Linearity was determined by using the pyroelectric detector to measure a neutral density filter transmission ratio as a function of max power density (lower axis) and total power (upper axis). The source was a He-Ne laser with a Gaussian beam and a $1/e^2$ intensity diameter of 2.0 mm. Each ratio was obtained on a single range of the power meter, eliminating possible range to range calibration errors, but increasing the scatter of the data. The curve is a subjective estimate based on the data points.

The results of figure 19 are undoubtedly a function of beam diameter. It is expected that with larger beams the nonlinearity threshold will be a larger total power and a smaller power density.

4.6 Power Limits

Three rather mediocre detectors were chosen for damage studies and a uniformity scan of each was made. The detectors were then exposed for 60 seconds to successively higher beam powers from the laser described in section 4.5. After each exposure a uniformity scan was made. At a power level of 12 mW total and a maximum irradiance of 700 mW/cm^2, all of the detectors survived without damage. A power level of 27 mW and 1.2 W/cm^2 caused about a 15% depression in the uniformity scan. Exposure to the unattenuated 55 mW (3.2 W/cm^2) beam resulted in about a 40% depression. Uniformity maps of a detector before and after exposure to the 55 mW beam are shown in figure 20.

Based on these results, a safe maximum irradiance for these detectors is 500 mW/cm^2. This conclusion was tested by putting a high responsivity (1.6 μA/W), very uniform (± 1%) detector in a 9 mW, 500 mW/cm^2 beam for one hour. A uniformity scan made after this exposure showed no damage. Although the detectors are not damaged at these high power densities, their response is highly nonlinear, and accurate measurements cannot be made. (See section 4.5).

4.7 Conclusions

The goal of this effort was to exploit certain properties of plastic pyroelectric detectors (viz. high detectivity, uniform response, broad spectral range) for the development of a laser power meter which was fast and could make meaningful measurements at low power levels. The resulting instrument meets these conditions, has good precision, and is simple to use.

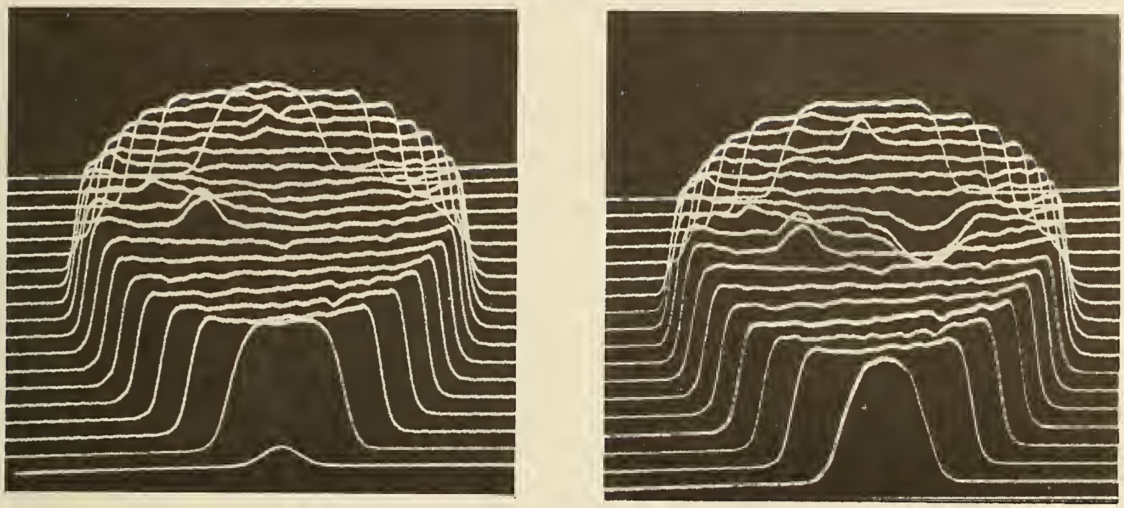

Figure 20. Uniformity maps of a detector before and after exposure to a 55 mW beam (3.2 W/cm^2 at center). Detector was of inferior quality prior to exposure.

At the present there are no other instruments with comparable performance in this power range and with broad spectral response. The most nearly comparable instruments are those based on high quality silicon photodiodes. These instruments have a substantial variation of response with wavelength and do not respond at all to radiation at wavelengths longer than 1 μm.

The problem of long term drift is significant but should not materially detract from the usefulness of the instrument when used as a transfer standard with regular calibrations.

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[8.] In addition to the instrument described in this note, we have developed a laser power meter which makes a continuous electrical calibration of the pyroelectric detector. See: Phelan, R. J., Jr. and Cook, A. R., "Electrically Calibrated Pyroelectric Optical-Radiation Detector", Appl. Optics 12, 2494-2500 (1973).

[9.] The use of a silicon diode power meter in these evaluations should in no way be construed as an endorsement. It is simply appropriate to insert a device with a presumably different set of characteristics into the evaluation.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A 1 cm^2 plastic (PVF_2) pyroelectric detector, developed in this laboratory, has been applied to measure low level laser power. The result is a compact instrument which has a low noise equivalent power (10^{-8} W/Hz$^{1/2}$), and fast response (1 s averaging time), and which is precise ($\sigma \sim \pm$ 1%), uniform ($\sim \pm$ 1%), and inherently free from short term drift. This note describes the fabrication of the detector, the design of the instrument, and the results of an extensive evaluation of three such instruments.

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Laser; power; pyroelectric.

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